High-Frequency Sound Interaction in Ocean Sediments: Environmental Controls

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LONG-TERM GOALS

Our long-term objectives are to provide a fundamental understanding of high-frequency acoustic-bottom interactions sufficient to predict acoustic scattering from the seafloor, penetration of acoustic energy into the seafloor, and propagation of acoustic energy within the seafloor. These acoustic models support performance prediction and tactical use of MCM sonar including buried mine detection by Synthetic Aperture Sonar (SAS), and also support shallow water ASW sonar systems.

OBJECTIVES

Provide statistical characterization of the environmental properties, especially the sediment volume properties, required to determine and model the dominant mechanisms controlling the penetration into and scattering from the seafloor of high-frequency acoustic energy. Determine the effects of biological, geological, biogeochemical, and hydrodynamic processes on the spatial distribution of sediment physical, geotechnical and geoacoustic properties at the experimental site. Develop predictive empirical and physical models of the relationships among those properties.

APPROACH

Participate in the SAX04 high-frequency acoustic experiments in the northeastern Gulf of Mexico. Provide statistical characterization of the environmental properties, especially the roughness and sediment volume properties, required to understand, model, and determine the relative importance of the dominant mechanisms controlling both penetration of high-frequency acoustic energy into the seafloor and scattering of high-frequency energy from the seafloor. Special emphasis is placed on the effect of sand ripples on SAS detection of buried targets. Measure and model the dispersive behavior of sediment sound speed and attenuation over the 1-400 kHz frequency band. Conduct in situ manipulative experiments to determine the effects of changing seafloor roughness and the presence of discrete scatterers on high-frequency acoustic scattering. Determine the effects of biological, geological, and hydrodynamic processes on the spatial and temporal distribution of sediment physical,

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geotechnical and geoacoustic properties. Develop predictive empirical and physical models of the relationships among those properties. Derive a fundamental understanding of the effects of sediment microstructure (porometric and grain properties) on fluid flow and geoacoustic properties.

WORK COMPLETED

The Seafloor Sciences Branch of the Naval Research Laboratory concentrated efforts on the sample analysis and data interpretation for the ONR Sediment Acoustic Experiment—2004 (SAX04) in the northeastern Gulf of Mexico during CY2004. The role of the Naval Research Laboratory is to provide statistical characterization of the environmental properties, especially the physical and geoacoustic properties, roughness, and sediment volume properties, required to understand, model, and determine the relative importance of the dominant mechanisms controlling both penetration of high-frequency acoustic energy into the seafloor and scattering of high-frequency energy from the seafloor. Special emphasis was placed on the effect of sand ripples on SAS detection of buried targets by the Applied Physics Laboratory (APL) at the University of Washington. We also measured and modeled the dispersive behavior of sediment sound speed and attenuation over the 1-400-kHz frequency band. In situ manipulative experiments were conducted to determine the effects of changing seafloor roughness on high-frequency acoustic scattering and to characterize and model the effects of biological, geological, and hydrodynamic processes on the spatial and temporal distribution of sediment properties, especially the effects of biological processes on rates of degradation of sand ripples. These data will be used to improved predictive empirical and physical models of the relationships among those properties and to derive a fundamental understanding of the effects of sediment microstructure (porometric and grain properties) on fluid flow and geoacoustic properties.

ENVIRONMENTAL MEASUREMENTS: Based on acoustic modeling requirements, values of the following sediment properties were measured during or following SAX04:

- Sediment grain properties: grain size distribution, shape and surface texture, and grain density
- Water properties: density, bulk modulus, viscosity, compressional speed measured and calculated from pore water temperature, salinity and pressure
- Porometry: porosity, pore body size distribution, pore shape, pore throat size distribution, pore body-pore throat correlations, grain contacts, permeability
- Sediment porosity and water content
- Sediment shear and compressional speed and attenuation
- 1-D (spatial and temporal variations) and 2-D seafloor roughness
- The distribution of discrete scatterers such as shells

Properties such as shear and compressional wave speed and attenuation, and seafloor roughness were measured in situ. Frame bulk and shear moduli and log decrements will be estimated from measured sediment geoacoustic properties. Measurement scales required to statistically characterize the heterogeneity of sediment properties such as bulk density, compressional wave speed and attenuation, and bottom roughness depend on the frequency of the acoustic phenomena being investigated: as small as a quarter of an acoustic wavelength or as small as 1 cm for penetration experiments and as small as 1 mm for scattering experiments.

RESULTS

Seafloor property measurements: Divers collected a total of 58 5.9-cm-diameter cores from throughout the experiment area in order to characterize the means and the spatial and temporal variability of geoacoustic and physical properties in the SAX04 experimental area. Although measured values of sound speed and attenuation fall within established ranges for archived data from similar medium quartz sands, fluctuations in measured values were observed in the data that can be explained by the pattern of storm events during the experiment. Three significant storm events occurred during the period in which cores were collected: a category-4 hurricane, a tropical storm, and an early-winter cold front. Following these events values of sound speed initially increased, but then later decreased; values of sound attenuation did not show this pattern, but were generally lower (mean = 92.1 dB/m) than values measured five years ago at the SAX99 site nearby (mean = 177.5 dB/m). Values of sediment sound speed measured at the SAX04 (mean velocity ratio = 1.162) were generally greater than those measured at the SAX99 site (mean velocity ratio = 1.155). Values of coefficient of variation for sediment sound speed were lower for SAX04 measurements (0.55%) than SAX99 measurements (0.70%). Lower values of sound attenuation measured at the SAX04 site was probably due to a lack or absence of shell fragments that may have been segregated by the sediment resuspension and settling during and after storms. Mud inclusions, or flasers, were a significant feature of the sandy sediments as a result of the storms.

Following the measurement of sediment sound speed and attenuation, 22 cores were selected for sectioning at 2-cm intervals for analysis of sediment porosity, bulk density, and grain density, and grain size distribution. Sediment porosity values (exclusive of high-porosity mud inclusions) from 22 of the 58 collected cores exhibit only small variations within the sandy sediment. Sediment mean grain size values (exclusive of mud layers) of the 22 cores assayed for porosity and bulk density also show little variation with sediment depth or location within the site. Sediment sorting also shows little variation with depth in the sediment or location. Moreover, the average value of sediment porosity at the SAX04 site, derived from 11 locations within the experiment site fall within the range of variation for each location (Fig. 1).

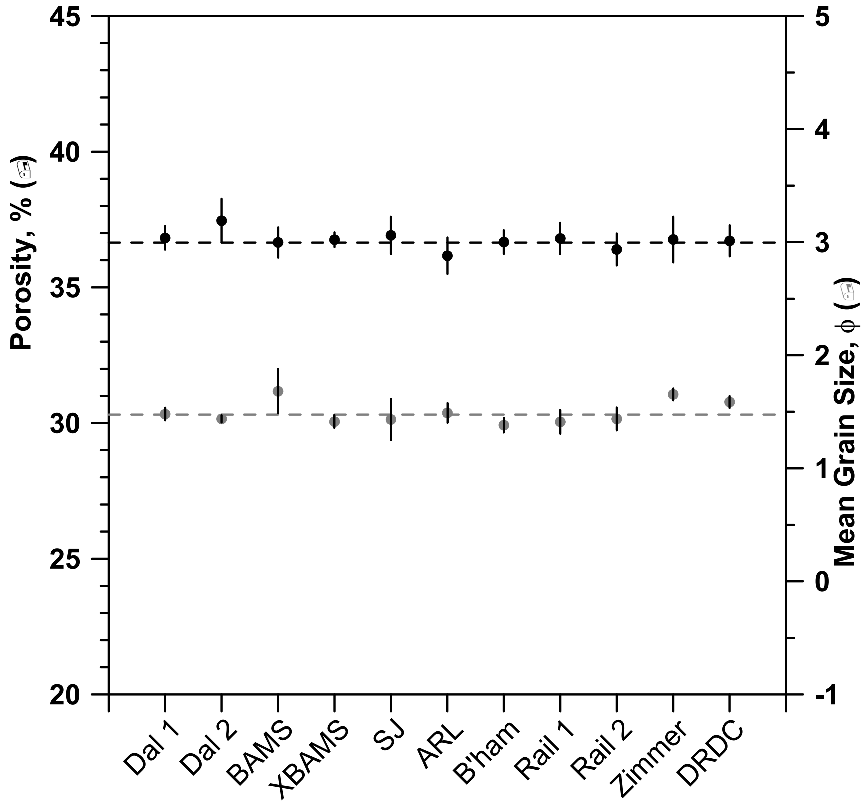

Figure 1. The 11 mean values of sediment porosity (left axis, black filled symbols) and mean grain size (right axis, gray filled symbols) are almost always within ±1 s.d of the site averages. Grain size is in phi (□) units, the negative base 2 logarithm of the grain diameter in mm.

Several of the long diver cores were impregnated with resin and scanned using X-ray microfocus computed tomography (XMCT) to determine fine-scale density heterogeneity as well as permeability. Porosity and permeability predictions made from pore information (pore size distributions, tortuosity, and connectivity) that was obtained from volumetric CT images, as well as from 2D CT slices, demonstrates that the sediment is homogeneous, both regionally at the field scale and locally at specific experimental sites (*e.g*., BAMS, Dalpod, XBAMS, Zimmer, Ship, Rail). These sediment properties are exhibit homogeneity at a dimension that is 6 times the grain scale or on the order of 4 mm. Sediment systems also were analyzed in terms of relative packing density for unconsolidated SAX04 sediments (d_{50} = 375 µm) by adjusting from minimum to maximum density by vibration in columns. A grain-based algorithm has been successfully furthered to evaluate and predict grain size distributions for these subangular to angular grains. The grain size data is in agreement with sieve data. Additionally, this algorithm provides data on grain shape (*e.g*., roundness and sphericity) grain coordination numbers, and grain contact areas to the limit of the voxel resolution. When sediments undergo consolidation and reordering in small column, in vitro experiments, these data provide a means to evaluate reordering, grain reorientation, as well as changes in contact numbers and contact areas. This work demonstrates the ability of XMCT to capture the micro-scale pore morphology and grain contacts and of a new grain-based algorithm to quantify morphology, which can be used to bound sediment physical and geoacoustic property values within a homogeneous, yet dynamic sand sediment.

Fifteen vibracores with an average length of 3.38 m were collected at the SAX04 site. Core analyses include MSCL core logging (gamma-attenuated density and p-wave velocity), X-radiography, core description and photography, and grain-size analysis. Preliminary results indicate that the upper 3 m of sediment is medium quartz sand with scattered carbonate shell hash and shell fragments. Mud lenses consistently occur that provide the sediment with a mottled texture. The facies in which the experiment was conducted is part of the MAFLA sand sheet and corresponds to the surficial palimpsest sediments derived from the eroded Pleistocene barrier island shoreline and extensively reworked by hydrodynamic events. Density profiles show a steady increase to a maximum of about 2.3 g/cm^3 between 0.5 and 2.0 m below the sea floor (bsf) before leveling off around 2.1 g/cm^3 near 3.0 m bsf. The sediment deeper than 3 m bsf shows much more variability in both the density and grain size profiles. Although largely characterized as fine-to-medium sand, the sediment contains a mix of mud and thin shells layers, including layers of wood pieces and highly organic material. It is likely that this sediment grades from a documented matrix-supported shell bed into previously described silt and clay layers 3-4 m in depth. These facies corresponds to the deposition of muddy organic-rich sediments influenced by both estuarine and marine processes, overlain by a transgressive sequence of eroded estuarine and shoreface deposits, and buried by Holocene autochthonous sedimentation.

In Situ Acoustic Measurements: During SAX04 we used three separate measurement systems to make velocity and attenuation measurements over a frequency range from 0.6 kHz to 400 kHz. Two of the measurement systems, covering frequencies from 0.6 to 200 kHz, made in situ measurements of the sands within the first meter below the seafloor. For frequencies below 20 kHz, signals produced by two acoustic sources at a range of offsets and azimuths from the array were recorded on a diver-implanted hydrophone and geophone array. At frequencies from 25 to 200 kHz, we made the measurements using a four probed piezoelectric array (ISSAMS). For comparison at the highest frequencies of 60 to 400 kHz, we measured the velocities and attenuation of 5 diver-collected cores with 4 separate pairs of oil-filled, peizoelectric transducers. Initial results for the sound speed measurements demonstrated a very stable acoustic velocity of approximately 1780 m/s above 10 kHz. Below 10 kHz the sound speed drops with decreasing frequency in a manner consistent with Biot theory. Processing of these data continue in order to obtain a more coherent picture of velocity dispersion in SAX04 sediment.

Acoustic scattering experiments from artificially manipulated seafloor surfaces: Divers set up treatment areas within the acoustic field of view of the 30-90 kHz APL Bottom-mounted rail system (STMS). Two experimental treatment areas were established 10 m from the base of the rail system. Backscattering strengths were measured as divers raked the treatment area. The treatments were designed to investigate scattering from fresh ripples over a range of acoustic frequencies. Acoustic measurements were made during two, 3-hour periods on October 18-19, 2004. The quasi-periodic ripple fields were raked by divers using a straight-edge surface milled to create tine spacings (ripple wavelength) of 1.91-cm and 3.0-cm. Ripple fields that were created perpendicular (90°) to the incident path of the acoustic waves had the only significant results in regard to enhanced scattering. Most of the experiments were conducted in conditions of very poor visibility (less than 30 cm) due to the aftermath of Hurricane Ivan (September 15-17, 2004). Thus these experiments initially were conducted without sufficient visibility to allow photogrammetry for the analysis of the 2D roughness spectra, which would aid model/data comparisons. In July 2006 we returned to re-create the raked roughness when water quality was improved enough for digital photogrammetry. Several digital stereo photographs were collected from the same STMS site where the 2004 manipulations were made. Of these, three were used to generate digital elevation models from which 2D roughness spectra were estimated and averaged. A 2D "slice" through average spectrum was made at the orientation across strike of the "ripples" from which a smooth, analytic model fit to the spectrum was made, using the second and third harmonic peaks. Over the 30-90-kHz range of interest the fit is pretty good and when the first-order, small-roughness perturbation model result is compared with the SAX04 data at a fixed grazing angle [28º], the agreement is quite startling, especially considering there are no free parameters. The tine spacing of 1.92 cm created a 30-dB peak in the spatial frequency domain where it was expected at 0.52 cycles/cm and the predicted increase in backscattering was in accordance with the measured increase.

IMPACT/APPLICATIONS

Understanding and modeling the phenomena of penetration of high-frequency sound at low grazing angles into the sea floor will aid in mine detection and classification for the navy.

TRANSITIONS

The results of this basic research are used in developing acoustic models for seafloor scattering. The database is potentially useful for inclusion in the NAVOCEANO shallow-water MIW sediment database.

RELATED PROJECTS

NRL has a companion 6.2 base program on high-frequency acoustic seafloor interactions. ONR Ripples DRI experiments were conducted concurrently with the SAX04 experiments. Todd Holland's Heterogeneous Environments ARO is being conducted in the same general area in the northeastern Gulf of Mexico.

PUBLICATIONS

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